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Final Report: MATHEMATICAL SCIENCE: A Homogenization-Driven Multiscale Approach for Characterizing the Dynamics of Granular Media and its Implementation on Massively Parallel Heterogeneous Hardware Architectures

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Objective: The goal of this project is to challenge and expand the current understanding of how numerical methods and emerging computational architectures can be used to predict the dynamics of dry granular systems. At mesoscale, the research will seek high fidelity Direct Numerical Simulation (DNS) methodologies that increase the size of the granular systems tackled in a fully resolved, discrete, fashion by three orders of magnitude. At macroscale, the research will investigate expeditious continuum representations suitable for granular dynamics

15. SUBJECT TERMS
computational nonlinear dynamics, many-body dynamics, friction and contact, numerical methods, differential variational problem, quadratic optimization

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UU	UU	UU	UU		DAN NEGRUT
					19b. TELEPHONE NUMBER: 608-890-0914

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Report Title

Final Report: MATHEMATICAL SCIENCE: A Homogenization-Driven Multiscale Approach for Characterizing the Dynamics of Granular Media and its Implementation on Massively Parallel Heterogeneous Hardware Architectures

ABSTRACT

Objective: The goal of this project is to challenge and expand the current understanding of how numerical methods and emerging computational architectures can be used to predict the dynamics of dry granular systems. At mesoscale, the research will seek high fidelity Direct Numerical Simulation (DNS) methodologies that increase the size of the granular systems tackled in a fully resolved, discrete, fashion by three orders of magnitude. At macroscale, the research will investigate expeditious continuum representations suitable for granular dynamics simulation. Finally, kinematically consistent homogenization and discretization approaches are envisioned to bridge the meso/macro scales and lead to variable resolution, hybrid continuum-discrete numerical solution methods.
Approach: The proposed approach builds on a multi-scale, i.e., mesoscale-macroscale, and multi-resolution, i.e., discrete-continuum, vision for the computer-enabled analysis of granular systems. At mesoscale, the computer is envisioned to play the role of a research instrument capable of providing detailed information about the state of the system: contact forces, element orientation, angular velocities, etc., that is subsequently used to synthesize new constitutive models and rheologies. At macroscale, a fine/coarse-graining, two-way scale bridging will lead to hybrid continuum-discrete approaches enabling the analysis of manufacturing and design engineering problems.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
05/31/2016	2.00	Hammad Mazhar, Toby Heyn, Dan Negrut, Alessandro Tasora. Using Nesterov's Method to Accelerate Multibody Dynamics with Friction and Contact, ACM Transactions on Graphics, (05 2015): 0. doi: 10.1145/2735627
05/31/2016	3.00	Radu Serban, Daniel Melanz, Ang Li, Ilinca Stanciulescu, Paramsothy Jayakumar, Dan Negrut. A GPU-based preconditioned Newton-Krylov solver for flexible multibody dynamics, International Journal for Numerical Methods in Engineering, (06 2015): 0. doi: 10.1002/nme.4876
05/31/2016	4.00	Arman Pazouki, Dan Negrut. Numerical investigation of microfluidic sorting of microtissues, Computers & Mathematics with Applications, (11 2015): 0. doi: 10.1016/j.camwa.2015.09.031
05/31/2016	5.00	Dan Negrut, Radu Serban, Hammad Mazhar, Toby Heyn. Parallel Computing in Multibody System Dynamics: Why, When, and How, Journal of Computational and Nonlinear Dynamics, (07 2014): 0. doi: 10.1115/1.4027313
05/31/2016	6.00	Arman Pazouki, Radu Serban, Dan Negrut. A High Performance Computing Approach to the Simulation of Fluid-Solid interaction Problems with Rigid and Flexible Components, Archive of Mechanical Engineering, (01 2014): 0. doi: 10.2478/meceng-2014-0014

TOTAL: 5

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Arman Pazouki	0.50	
Hammad Mazhar	0.50	
Toby Heyn	0.50	
FTE Equivalent:	**1.50**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Dan Negrut	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ......

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ......

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ......

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Toby Heyn	
Hammad Mazhar	
Arman Pazouki	
Total Number:	**3**

Names of other research staff

NAME	PERCENT_SUPPORTED
Radu Serban	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment.

Technology Transfer

See attachment.

1. Science

a. What is the mathematical objective of your project? What question are you trying to answer?

The mathematical objective was to identify numerical methods that can be used to determine the evolution of many-body dynamics systems. For rigid-body dynamics with friction and contact, the computational bottleneck is the solution of a large scale optimization problems. In this context, the question that I'm trying to answer is: How can I solve expeditiously and robustly a large semi-definite quadratic problem with conic constraints (SD-QPwCC) in millions of variables?

b. What are the challenges in doing this? What makes it difficult?

The source of the SD-QPwCC is the simulation of many-body dynamics in the presence of friction and contact. As such, the dimension of the optimization problem is very large. For instance, in one cubic meter of sand there are about two billion elements. This problem would have about 8 billion contacts, which leads to a QPCC in approximately 25 billion variables. To date, the largest problem that we have solved has approximately 40 million variables. The challenging part is finding numerical methods that are (i) robust to handle problems on this scale; i.e., we can actually solve the problem, and (ii) can be parallelized for leveraging advanced computing; i.e., we can solve the problem reasonably fast so that we can put it to good use in conjunction with practical problems.

c. What is the scientific opportunity that is enabling you to make progress in this difficult area?

Recent advances in optimization techniques provided the motivation to investigate new methodologies for the solution of large many-body dynamics problems. Also, there is great impetus behind the topic of advanced computing – everything from emerging parallel computing hardware to new libraries for CPU/GPU parallel computing. The introduction of new solution methods that leverage new hardware have allowed us to reduce simulation times by a factor of 25 over the last five years. The research conducted during this project has provided support to make this leap possible. We are now capable of analyzing significantly larger problems that open up new avenues for computing-enabled discovery and innovation.

d. Please attach one (or a few if you wish) graphic that best represents what your project is about. People are visual; one graphic can help them grab onto your project much quicker.

Rather than attaching a graphic, I'm providing a link where there are more than 150 movies that we have generated, most of them over the last three years. These movies can be downloaded. All the recent movies use the numerical methods and software infrastructure advances made possible by the research sponsored by Dr. Myers. Still images from any movie at the links below can be provided upon request:

https://vimeo.com/uwsbel

http://sbel.wisc.edu/Animations/

2. Collaborations

a. Name and give organization of anybody in the Army/DoD/govt who you have collaborated with in the course of this project.

- Dr. Paramsothy Jayakumar of US Army TARDEC
- Mr. Mike Letherwood of US Army TARDEC
- Dr. Mihai Anitescu of Argonne National Lab
- Dr. James Schneider of US Navy NAVFAC EXWC

b. Describe the nature of the collaboration. Include co-authoring with them, giving talks at their place, inviting them to your school, getting scenarios or data or ideas from them, conducting joint workshops or seminars, etc.

Dr. Jayakumar: I have had extensive collaborations with him. I have co-authored several journal and conference manuscripts with him and he and several of his colleagues from US Army TARDEC have had multiple visits to my lab. I have visited with him at US Army TARDEC on several occasions and I have given several seminars there over the last three years (see list of talks provided in this document). My lab is in the process of organizing a joint "Machine-Ground Interaction Consortium" (MaGIC) meeting in Novi, Michigan, right next to TARDEC on August 3-4, 2016 in collaboration with Dr. Jayakumar.

Mr. Letherwood: My interaction with Mr. Letherwood has been very similar to my collaboration with Dr. Jayakumar.

Dr. Mihai Anitescu: We worked together on modeling approaches for granular material. I provided material for his presentations and he served on the PhD thesis committee of one of my students (Toby Heyn) who was funded through this ARO project.

Dr. James Schneider: He attended one of the meetings organized by the PI in Madison, see MaGIC meeting below. He is interested in using the software infrastructure Chrono that embeds the numerical solution advances made under this project.

c. If any of your students, postdocs, or faculty were hired by the Army or DoD, please give details.

Graduate student Daniel Melanz is currently employed by US Army TARDEC and he is anticipating graduating with a PhD degree in May 2016.

3. Transitions: Describe anything from this project that you transitioned to anybody else (whether Army, DoD, govt, commercial, or other).

a. Who did you give it to, and what is their organization?

The research that was funded by Dr. Myers led to a numerical method that is now the workhorse in a frictional contact solver used in a physics-based simulation engine called Chrono. Chrono is an open source parallel computing infrastructure that is being developed under a $1.8 million project funded through an Army Rapid Innovation Fund award that is managed by Dr. Jayakumar of US Army TARDEC. Chrono has more than 200,000 lines of code and runs rigid body dynamics, flexible body dynamics, and fluid-solid interaction problems. The funding from Dr. Myers' project allowed us to further develop the code.

Links:

- https://github.com/projectchrono/chrono
- http://projectchrono.org/chronoengine/

Chrono is also currently undergoing testing by Oshkosh Corporation. They are evaluating Chrono to understand whether it will allow them to accurately simulate the JLTV on deformable terrain. There is no other software capability today, commercial or open source, which can provide this type functionality. In addition to being used for off-road mobility studies, Chrono is being used by UC-San Diego for the motion of molecules as well as by NASA, by US Army ERDC, by Statoil in Norway, etc. for various applications.

b. What did you give them? Code, papers, algorithms...

We provided free open source code, papers, algorithms, models, presentation, and software documentation. We also ran a tutorial on how to use our software, which was attended by individuals from US Army TARDEC and ERDC.

c. What eventual application might this enable?

Chrono has been selected to participate in a NATO-run process to recommend what simulation tool(s) should replace the current NATO Reference Mobility Model (NRMM) which has been used for mobility go/no-go studies for more than four decades. Beyond this, Chrono has already been used to study additive manufacturing, oil spill capping designs, vehicle dynamics, etc.

d. What was your scientific accomplishment that enabled this?

Development of

- New numerical techniques
- New modeling approaches (cohesion)
- Techniques for collision detection between deformable geometries
- Design of algorithms that can leverage parallel computing (matrix free, GPU computing, AVX support)

4. Awards/honors: By you and anybody funded by this project: students, postdocs, faculty ...

a. Include awards, prizes, Fellow/Society election, best paper prizes (especially student),elected positions, papers in Science or Nature, ...

- As of October of 2015, I am the Chair of the Technical Committee on Multibody System and Nonlinear Dynamics of the American Society of Mechanical Engineers. I'll serve in this capacity for two years.
- I serve on the editorial board of three journals
- I have been awarded a 2014-2016 Vilas Fellowship for recognition of contributions to research made at the University of Wisconsin-Madison. This is one of the most prestigious research accolades at the University of Wisconsin-Madison
- I have been awarded the NVIDIA CUDA Fellow status for contributions in parallel computing on the GPU six consecutive times
- I have been awarded the 2016 College of Engineering "Equity and Diversity Award" at UW-Madison
- I have been invited to give several keynote talks in Europe/North America/Asia, one of them in conjunction with a NATO meeting on advanced computing in ground mobility topics
- I was a member of the following steering committees:
  - 2014 International Conference on Multibody System Dynamics, Soul, S. Korea
  - 2016 International Conference on Multibody System Dynamics, Montreal, Canada
- I was the conference chair for the International Conference on Multibody Systems, Nonlinear Dynamics, and Control (MSNDC),
  - 10^{th} edition, Buffalo, NY, 2014
  - 12^{th} edition, Charlotte, NC, 2016

5. Metrics related to your grant:

a. # peer-reviewed papers (related to this grant)

- Hammad Mazhar, Toby Heyn, Dan Negrut, and Alessandro Tasora. 2015. Using Nesterov's Method to Accelerate Multibody Dynamics with Friction and Contact. ACM Trans. Graph. 34, 3, Article 32 (May 2015)
- Radu Serban, Daniel Melanz, Ang Li, Ilinca Stanciulescu, Paramsothy Jayakumar, Dan Negrut. A GPU-based preconditioned Newton-Krylov solver for flexible multibody dynamics, International Journal for Numerical Methods in Engineering (2015), Volume: 102, Issue: 9,
- Arman Pazouki, Dan Negrut. Numerical investigation of microfluidic sorting of microtissues, Computers & Mathematics with Applications, Available online 3 November 2015, ISSN 0898-1221

- D. Negrut, R. Serban, H. Mazhar, T. Heyn, "Parallel Computing in Multibody System Dynamics: Why, When and How", ASME Journal of Computational and Nonlinear Dynamics, Issue 4, 2014
- A. Pazouki, R. Serban, and D. Negrut, "A high performance computing approach to the simulation of fluid-solid interaction problems with rigid and flexible bodies", Archive of Mechanical Engineering, Volume 61, Issue 2 (Aug 2014)

b. manuscripts (related to this grant)

- Daniel Melanz, Luning Fang, Paramsothy Jayakumar, Dan Negrut. "A comparison of numerical methods for solving multibody dynamics problems with frictional contact modeled via differential variational inequalities" (manuscript attached, to be submitted to Journal of Computational Physics in February of 2016).
- If this counts, there is a series of technical reports that we produced and are related to this project, http://sbel.wisc.edu/Publications/

c. presentations.

All presentations mentioned below acknowledged the Army funding support:

1. "On the Use of Computer Modeling to Characterize the Dynamics of Large Particulate Systems," Iowa State University, Ames, IA, November 30, 2015
2. [Keynote] "Ground Vehicle Mobility: The Long Term View," NATO Applied Vehicle Technology Committee Meeting, Prague, Czech Republic, October 15, 2015
3. "Chrono-Gazebo: An open source integrated framework for intelligent vehicle on/off-road mobility analysis," NATO Advanced Vehicle Technology Committee meeting, Prague, Czech Republic, October 14, 2015
4. "On the Use of Computer Modeling to Characterize the Dynamics of Large Multi-Body Systems," Danish Center for Applied Mathematics and Mechanics and University of Aarhus, Aarhus, Denmark, September 23, 2015
5. [Keynote] "On the Use of Computer Modeling to Characterize the Dynamics of Large Particulate Systems," Particle Simulation Conference, Erlangen University, Germany, September 21, 2015
6. "Using Parallel Computing in Computational Dynamics," Darmstadt Technical University, Germany, August 24, 2015
7. "Project Chrono - An open source framework for the dynamics analysis of many-body systems," Polytechnic Institute of Bucharest, Bucharest, Romania, June 19, 2015
8. "Project Chrono - An open source framework for the dynamics analysis of many-body systems," US Army TARDEC, Warren, Michigan, June 15, 2015
9. "Project Chrono - An open source framework for the dynamics analysis of many-body systems," Oshkosh Corporation, June 3, 2015
10. [Keynote] "From Granular Dynamics to Fluid-Solid Interaction and From Large Optimization Problems to Solving Sparse Linear Systems," High Performance Computing In Science and Engineering Conference, IT4Innovations National Supercomputing Center, Czech Republic, May 25, 2015
11. "Project Chrono - An open source framework for the dynamics analysis of many-body systems," INRIA, Grenoble, France, January 22, 2015
12. "Project Chrono - An open source framework for the dynamics analysis of many-body systems," Technical University Munich, Germany, January 20, 2015
13. "The Interplay between Frictional Contact and High Performance Computing in Many-Body Dynamics Simulation," NVIDIA, Santa Clara, April 17, 2014

14. “On Fast Computers and Their Use in Mechanical Engineering: From the Dynamics of Granular Material to the Motion of the Mars Rover,” Stanford University, April 18, 2014
15. “Getting Shape into Computational Dynamics. Getting Computational Dynamics in Shape,” Department of Mechanical Engineering, University of Michigan, April 7, 2014
16. “A parallel multi-physics library for rigid-body, flexible-body, and fluid dynamics,” 2014 Rice Oil & Gas High Performance Computing Workshop, Rice University, Houston, TX, March 2014
17. “On Fast Computers and Their Use in Mechanical Engineering,” talk at the Wisconsin Institute for Discovery - Doing Optimization at Wisconsin (WID-DOW) seminar series, University of Wisconsin-Madison, WI, January 2014
18. “High Performance Computing in Multibody Dynamics,” BIRS Workshop on Computational Contact Mechanics: Advances and Frontiers in Modeling Contact, Banff International Research Station, Canada, February 2014
19. “A Discussion of Numerical Methods for Fast Simulation of Many-Body Dynamics Problems with Frictional Contact,” 2013 Workshop on Multibody System Dynamics, University of Illinois at Chicago, IL, August 10, 2013
20. “On Fast Computers and Their Use in Mechanical Engineering: From the Dynamics of Granular Material to the Motion of the Mars Rover,” Fraunhofer Institute for Industrial Mathematics ITWM, Kaiserslautern, Germany, November 13, 2013
21. “Recent Progress in the Use of High Performance Computing in Computational Dynamics,” Caterpillar, Moline, IL, March 2014
22. “Advanced Computing in Computational Dynamics,” MSC.Software, Ann Arbor, MI, January 2014
23. “Overview of Computational Dynamics Research at the Simulation-Based Engineering Lab,” Trek Bicycle, Waterloo, Wisconsin, Dec. 16, 2013
24. “On Fast Computers and Their Use in Mechanical Engineering: From the Dynamics of Granular Material to the Motion of the Mars Rover,” Dassault Systems, Paris, France, November 12, 2013
25. “On Fast Computers and Their Use in Mechanical Engineering: From the Dynamics of Granular Material to the Motion of the Mars Rover,” IHC Merwede Group, Rotterdam, The Netherlands, November 11, 2013
26. “Calibration and Validation of a Lower-Order Soil Compaction Model under Non-Uniform Tire Loads Applied By A Dynamic Vehicle Model.” J. Madsen, P. Ayers, D. Negrut. ISTVS 2013, Nov. 3-6, Tampa, FL.
27. “Evaluation of Tire/Soil Contact Models to Predict Vehicle Mobility and Soil Compaction on a Reduced-Order Terrain Model”, J. Madsen, D. Negrut. ASME IDETC 2014, Aug. 17-20, Buffalo, NY.
28. “Chrono: An Open Source Parallel Simulation Framework for Many-Body Dynamics Applications.” D. Negrut, H. Mazhar, R. Serban, D. Melanz, A. Pazouki, D. Kaczmarek, P. Jayakumar, A. Tasora. 17th U.S. National Congress on Theoretical & Applied Mechanics, June 15-20, 2014, East Lansing, Michigan.
29. “Numerical investigation of flow cytometry using a microfluidic technique”, A. Pazouki, D. Negrut. The 11th International Conference for Mesoscopic Methods in Engineering and Science, July 15, 2014, New York City, New York.

30. “A fluid-solid interaction approach for the simulation of rigid and deformable bodies in Newtonian fluid”, A. Pazouki, R. Serban, D. Negrut. ASME 2014 International Design and Engineering Technical Conferences & Computers and Information in Engineering Conference, August 20, 2014, Buffalo, New York.
31. “An Analysis of Primal-Dual Interior Point Method for Computing Frictional Contact Forces in a Differential Inclusion-based Approach for Multibody Dynamics”, L. Fang, T. Heyn, D. Melanz, H. Mazhar, D. Negrut. ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC), August 17-20 2014, Buffalo, NY
32. “A Fluid-Solid Interaction Approach for the Simulation of Polymer Motion in Newtonian Fluid”, A. Pazouki, R. Serban, D. Negrut. 3rd International Conference on Multibody System Dynamics (IMSD 2014), June 30 - July 3, 2014, Busan, Korea
33. “A GPU-Based Preconditioned Newton-Krylov Solver for Flexible Multibody Dynamics”, R. Serban, D. Melanz, A. Li, P. Jayakumar, D. Negrut, ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC), August 17-20 2014, Buffalo, NY
34. “Chrono::Render – A Graphical Visualization Pipeline for Multibody Dynamics Simulations.” A. Bartholomew, F. Guttierrez, D. Kaczmarek, H. Mazhar, D. Negrut. ASME Buffalo Conference, August 17-20, 2014, Buffalo, New York
35. “Gauging military vehicle mobility through many-body dynamics simulation,” D. Melanz, H. Mazhar, D. Negrut. ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC), August 17-20 2014, Buffalo, NY.
36. “Gauging military vehicle mobility through many-body dynamics simulation,” D. Melanz, H. Mazhar, D. Negrut. 3rd Joint International Conference on Multibody System Dynamics (IMSD 2014) and the 7th Asian Conference on Multibody Dynamics (ACMD 2014), June 30 - July 3 2014, Busan, Korea.
37. “A Comparative Study of Penalty and Complementarity Methods for Handling Frictional Contact in Large Multibody Dynamics Problems,” D. Melanz, R. Serban, H. Mazhar, P. Jayakumar, D. Negrut. 17th U.S. National Congress on Theoretical & Applied Mechanics (USNC/TAM), June 15-20 2014, East Lansing, MI.
38. “A Multibody Dynamics-Enabled Mobility Analysis Tool for Military Applications,” D. Melanz, H. Mazhar, D. Negrut. Society of Automotive Engineers (SAE) World Congress, April 8-10 2014, Detroit, MI.
39. “Chrono::Flex - A Flexible Multibody Dynamics Framework on the GPU,” D. Melanz, R. Serban, A. Li, D. Negrut. GPU Technical Conference (GTC 2014), March 24-27 2014, San Jose, CA.
40. “Project Chrono: Gauging military vehicle mobility through many-body dynamics simulation,” D. Melanz, H. Mazhar, D. Negrut. Computational Contact Mechanics: Advances and Frontiers in Modeling Contact (BIRS Workshop), February 16-21 2014, Banff, Canada.
41. “Studying the Effect of Powder Geometry on the Selective Laser Sintering Process,” H. Mazhar, J. Bollmann, E. Forti, A. Praeger, T. Osswald, D. Negrut, Society of Plastics Engineers (SPE) ANTEC, April 28-May 31 2014, Las Vegas, NV
42. “A Simulation Based Approach to Study How Powder Shape Influences The Selective Laser Sintering Process,” H. Mazhar, J. Bollmann, E. Forti, A. Praeger, T. Osswald, D. Negrut,

International Conference on Multibody System Dynamics (IMSD), June 30-July 3 2014, Busan, South Korea

43. "Chrono: a parallel multi-physics library for rigid-body, flexible-body, and fluid dynamics," A. Tasora, H. Mazhar, A. Seidl, D. Melanz, A. Pazouki, J. Madsen, D. Kaczmarek, R. Serban, D. Negrut, International Conference on Multibody System Dynamics (IMSD), June 30-July 3 2014, Busan, South Korea
44. "Beyond Jacobi and Gauss-Seidel: A First Order Nesterov Method for Multibody Dynamics with Frictional Contact" at the BIRS Workshop, "Computational Contact Mechanics: Advances and Frontiers in Modeling Contact", Feb 15-Feb 21 2014, Banff, Alberta

d. patents submitted (funded by this grant)

None.

e. # grad students/yr (funded by this grant)

one/year, year 1 and 2

- Toby Heyn
- Arman Pazouki

f. #postdocs/yr (funded by this grant)

Assistant Scientist: 1/year, year 3 (Radu Serban).

g. PhD degrees awarded (funded by this grant)

Two: Toby Heyn and Arman Pazouki.

h. MS degrees awarded (funded by this grant)

None.

6. Anything else of note we should know about and tell the BOV about?

Three years ago I organized a Machine-Ground Interaction Consortium (MaGIC) meeting in Madison, WI that was set up to facilitate the transfer of technology from academia to industry/gov. labs. This effort has continued as a series of twice a year meetings with a continually increasing number of participants. We are well positioned to support a vigorous technology transfer effort since all of our code/papers/tech reports are in a public repository (GitHub) or are on the lab website and as such are open to everyone. Our simulation engine is open source and free for unrestricted use, distribution, copying, editing, and resale. In 2015 we organized the third and fourth editions of MaGIC, which brought together industry, government, and academia members interested in understanding how advanced computing is shaping the area of vehicle mobility. So far, the list of participants to these MaGIC events have included: US Army TARDEC, US Army ERDC, US Marine Crops, Open Source Robotics Foundation, Jet Propulsion Laboratory, NASA, Japan Aerospace Exploration Agency, Caterpillar, P&H Mining, MSC.Software, Simertis Gmbh, BAE Systems, Eaton Corporation, Rescale, Red Cedar Technology, NVIDIA, Nevada Automotive Test Center, Harley-Davidson Motor Company, Oshkosh Corporation, John Deere, Statoil (Norway), Proctor and Gamble, Cooper Industries, GlaxoSmithKline, HR Wallingford LTD, Motionport, Altair, Hendrickson, Japan Department of Defense, Intuitive Machines, Energid Technologies, SmartUQ, SimLab Soft, Progeneric Systems, Function Bay, Trek Bicycles, Dynamic Simulation Technologies, University of Wisconsin-Madison, Johns Hopkins University, University of Iowa, Georgia Institute of Technology, University of Parma (Italy), Politecnico di Milano (Italy), MIT, Darmstadt University (Germany), University of Illinois at Chicago, University of Aarhus (Denmark), Beijing Technical

Institute (China), Fraunhofer Institute for Industrial Mathematics at Kaiserslautern University (Germany), and Inha College (S. Korea).